Development of a Space-Rated Proton Exchange Membrane Fuel Cell

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Abstract:

Power systems for human spacecraft have historically included fuel cells due to the superior energy density they offer over battery systems depending on mission length and power consumption. As space exploration focuses on the evolution of reusable spacecraft and also considers planetary exploration power system requirements, fuel cells continue to be a factor in the potential system solutions.

Substantial efforts are currently underway in the commercial markets to produce a proton exchange membrane (PEM) fuel cell capable of meeting terrestrial power demands in residential, commercial, and automotive applications. However, there are unique characteristics of spaceflight that can only be dealt with through specific engineering solutions. Reducing development, production, and maintenance costs while maximizing system reliability and life are goals of the fuel cell effort currently underway at the Johnson Space Center.

From a systems perspective, removing product water from the cell stack and separating the water from the oxygen gas stream in a PEM fuel cell are two critical functions. One method to remove product water from the cell stack and subsequently separate the product water from the oxygen involves using components with no moving parts--a gas ejector and membrane gas-water separator. Tests are currently underway at the Johnson Space Center to evaluate and refine gas ejectors to satisfy the fuel cell requirement to circulate cathode reactant gas (oxygen) at 1 to 3 times the stoichiometric consumption flow rates in order to adequately remove water from the cathode. A water-gas separator utilizing hydrophobic and hydrophilic materials is also being evaluated to perform the function of separating the water from the oxygen gas stream. The gas ejector and membrane water separator together with a PEM fuel cell designed for external water separation form one basis of a system configuration for spaceflight operation. By selecting fluid recirculation and water separation components which are passive in nature, the overall reliability and safety of the system is expected to increase. Analytical and experimental evaluations are continuing on the fuel cell components, including cell stacks, with the goal of developing a comprehensive design basis for a fuel cell powerplant capable of delivering 20 kW at approximately 28 vdc. Through the select critical component refinement in work at the Johnson Space Center, engineers are improving the readiness and reducing the technical and cost risks of a PEM fuel cell capable of operating in a space environment.

NOMENCLATURE

A - Area (cm^2)
M - Mass Flow Rate (kg/sec)

P - Pressure (kPa)
Rgc - Gas Constant
T - Temperature ($^{\circ}$C)
V - Volume (cm^3)
d - Diameter (cm)
k- Specific heat ratio
δ - Loss Factor
η - Fitted Mass Factor

I. INTRODUCTION

The PEM fuel cell power plant in the Space
Shuttle must operate when subjected to the
environments specified in Table 1.

Table 1
Space Shuttle PEM Fuel Cell
Environmental Requirements

Temperature	-53.9 $^{\circ}$C to +87.8 $^{\circ}$C (-65°F to +190°F)
Atmospheric Pressure	760 Torr to 10^{-10} Torr
Shock	1.5 g, 260 ms pulse width
Random Vibration	2.25 grms from 20 to 2000 Hz
Acceleration	0 to 3.3 g

A schematic of a fuel cell power plant is
shown in Figure 1. The PEM fuel cell
performance is determined primarily by the
membrane polarization curve, an example
of which is shown in Figure 2. Product
water management in a PEM fuel cell has
been addressed using one of two methods.
The first involves removal of product water
from the cathode using water wicking
materials and the second relies on excess
oxidizer flow to entrain and remove the
product water from the cathode. Tests and
analyses of components required for the
latter product water removal technique have

been performed and are underway at the
Johnson Space Center (JSC). This paper
describes the design approach to satisfy the
PEM fuel cell performance requirements,
characteristics of components tested to date,
and conclusions regarding the performance
and analytical estimates.

II. DESIGN ISSUES FOR A SPACE PEM FUEL CELL POWERPLANT

As previously mentioned, substantial R&D
is being completed for terrestrial based
PEM Fuel Cell Powerplants (FCPs)
(Reference 1). However, there are some
significant and unique design parameters
that must be addressed in a space-rated
PEM FCP. Some of the design parameters
that have been identified are:

1. Application for power system. It is
   important to know what is the larger
   system to which the fuel cell will be
   integrated, such as a Space Shuttle,
   Mars Planetary Manned Transit vehicle,
   surface rover, or lunar base utility
   power system. This will affect the
   environment (e.g. temperature, gravity,
   water discharge pressure) in which the
   FCP is required to operate.
2. Power levels and voltage range. These
   parameters are used to set the basic size
   of the fuel cell stack using polarization
   curves as shown in Figure 2. The Space
   Shuttle currently requires power from
   its three parallel FCPs at voltages from
   27.5 to 32.0 VDC. There are some
   future spacecraft designs that may
   require 120 or 270 VDC power—
   normally for electromechanical
   actuators or electric-motor-driven
   hydraulic systems.
3. Reactant supply. While most terrestrial
   fuel cell transportation systems will rely
   on hydrocarbon based fuels and air as
   oxidant, NASA's manned spacecraft
   typically use pure O2 and H2 for fuel
   cells, propulsion, and crew breathing.

4. Cooling. Thermal management in a space-rated PEM FCP is extremely critical. There are a variety of heat transfer fluids and methods that must be analyzed for performance and material compatibility.

5. Stack humidification. There are several methods of providing stack humidification to the reactant gases, such as: internal to the stack, external to the stack, active (water pumped or spray injected), or passive.

6. Product water removal. For most ground based applications, product water is swept out of the stack with an excess flow of gases (normally air). For a space PEM FCP, this technique can be used as well as one where the water is removed internal to the stack. The internal removal technique can also be used in a space PEM FCP.

7. Product water separation. For ground based applications, the product water can be discharged to the environment. For space applications, the product water is a valuable by-product and is recovered for use as crew potable water or for cooling. Centrifugal water separators have been used in the past to separate liquid water from a gas stream in the micro-gravity of space. This requires mechanically moving parts, which have been shown to be a limiting life item on FCP designs. In the case of a PEM FCP, a safety concern is also associated with the rotating machinery in the oxygen environment. Another potential method uses the selective placement of hydrophilic and hydrophobic membranes to "passively" separate the water from circulating oxygen gases.

8. Reactant pumping. As stated above, the oxygen reactants in a space PEM FCP may need to be recirculated. There are many different ways to pump reactant gases. One of these is with the use of an ejector, as opposed to a positive displacement pump or rotating compressor. An ejector uses a high velocity gas from a high pressure source to entrain and pump gas from the suction port to the exhaust port. For the fuel cell, the high pressure supply gas is the same as the consumption gas stream in the fuel cell.

9. Operational life, maintenance, and diagnostics. Currently, specifications for the PEM fuel cell upgrade for the Space Shuttle call for a 10,000 hour, maintenance-free operational life. For long ranging missions, such as to Mars (Reference 2), the ability to reliably operate for thousands of hours and hundreds of cycles will no doubt be a key advantage to the use of PEM fuel cells.

III. JSC SPECIFIC SPACE PEM FCP DESIGN

There could be many different system configurations that might be arrived at using basic PEM fuel cell stack and accessory section building-block elements. The space rated PEM FCP design effort at JSC is concentrating on the particular application of the Space Shuttle upgrade. This design also has applicability to the Reuseable Launch Vehicle, Lunar/ Planetary Surface Rovers, and Planetary Transit Vehicle Power Systems. Multi-vehicle compatibility is being kept as an important secondary objective.

The particular configuration under development at JSC is shown in Figure 1. The stack is a 15-cell, 4-kW PEM fuel cell stack manufactured by Energy Partners, Inc. A representative voltage vs. current density curve is shown in Figure 2. This data was obtained in 1996 with the stack operating at temperatures of ~38-43°C (100-110°F). With increases in operating temperature that will be obtained with the system shown in Figure 1, this fuel cell's performance will increase significantly. The stack

incorporates an internal pre-humidificatation assembly and uses the common excess oxygen recirculation method to remove product water from the stack.

The system will use ejector-based reactant pumps to accomplish both fuel and oxidant gas recirculation. Two types are planned for use. The first type has been designed, fabricated, and tested in-house using engineering expertise from several organizations at the NASA-JSC. The second type is a commercially-available Mini-Eductor from Fox Valve Development Company. Two of these Fox Mini-Eductors will be used in parallel to provide hydrogen reactant recirculation while one of the NASA-JSC ejectors will be used to provide oxygen reactant recirculation.

Water separation from the recirculating oxygen stream will be accomplished using a passive, membrane based separator manufactured by Hamilton Standard.

IIIa. EJECTOR

The use of a gas ejector to recirculate fuel cell reactants provides a passive, reliable device offering long service life. The concept of using a gas ejector in fuel cell applications has been pursued by Ballard Power Systems (Reference 3) and NASA-Johnson Space Center (Reference 4). The schematic of an ejector is shown in Figure 3. Extensive analysis of ejector performance and determination of ejector flow as a function of dimensions and system pressures has been described in References 5 and 6. From Reference 5, the relationship between the input pressure to the gas ejector and mass flow into the fuel cell, M_7, is represented by the equation

$$(1)$$

$$P2 = \frac{-\left[-4P_7^{\frac{k-1}{k}} \cdot \left(A3 \cdot \frac{\phi \cdot \eta}{M_7}\right)\right] + \sqrt{\left[-4 \cdot P_7^{\frac{k-1}{k}} \cdot \left(A3 \cdot \frac{\phi \cdot \eta}{M_7}\right)\right]^2 - 4 \cdot \left[2 \cdot \left(\frac{A_5}{A_3}+1\right) \cdot P_7^{2\left(\frac{k-1}{k}\right)} \cdot \left(A3 \cdot \frac{\phi \cdot \eta}{M_7}\right)^2 \cdot \left[1 - \delta - \frac{\Delta P \cdot 2 \cdot P_7}{\left[\frac{R_g \cdot T_7 M_7^2}{A_5^2}\right]}\right]\right]}}{2 \cdot \left[2 \cdot \left(\frac{A_5}{A_3}+1\right) \cdot P_7^{2\left(\frac{k-1}{k}\right)} \cdot \left(A_3 \cdot \frac{\phi \cdot \eta}{M_7}\right)^2\right]}^k$$

The ejector dimensions were d3=0.101 cm (0.04 inch) and d5 = 0.31 cm (0.122 inch.) Using the relationships and coefficients for the loss factor, mass coefficient, and modified fitted mass factor as described in References 5 and 6, the predicted input pressure P2 was computed and compared with measured data. Test data for the ejector is shown in Table 2. In general, as the pressure drop across the ejector increases, the expected recirculation flow will decrease. The performance illustrated in Table 2 infers that a pressure of 422 kPa (61.2 psia) is required at d2 in order to supply sufficient motive pressure to meet a fuel cell consumption of 12.9 slpm, a recirculation flow of 38.2 slpm across a

pressure drop of 11.5 kPa (1.67 psid), and a   fuel cell pressure of 246.2 kPa (35.7 psia.)

Table 2
Gas Ejector Performance Data

M_7	M_7/M_3	P_7	T_7	dp	P_2 measured	P_2 calculated	error
kg/sec		kPa	R	kPa	kPa	kPa	%
9.9e-4	4	246.2	530	11.46	421.1	350	16.8
2.9e-4	1.03	242.2	530	36.3	478.8	477.6	.25
5e-4	1.02	345.7	530	94.3	956.4	953.9	.26
2.1e-3	4.2	328.2	530	45.1	954.7	1203.2	26

IIIb. PASSIVE WATER SEPARATOR

The breadboard zero-g passive water separator manufactured by Hamilton Standard consists of 12 circular sets of hydrophobic and hydrophilic membranes, manifolded and stacked between two large stainless steel endplates. The separator also includes a dome loaded Back Pressure Regulator (BPR) which will allow the water to be discharged to ambient pressure. The BPR also controls the water pressure inside the separator to about the same pressure as the incoming gas. This will preclude the potential to tear the membranes due to a high delta pressure (ΔP). A picture of the separator is shown in Figure 4.

The test article was designed to separate up to 100 slpm of gas and 125 ccm of water at operating pressures of 0-517 kPa (0-75 psia) and temperatures between 4.4-93.3°C (40-200°F). In addition, the water separator would perform this function with a pressure drop across the gas membrane of < 20.7 kPa (3 psi).

A test stand was constructed at the JSC that combined gaseous nitrogen and deionized water into a 2-phase stream at the proper pressure and temperature and fed it to the separator (see Figure 5). This would simulate the flow of gas and entrained water droplets exiting the reaction sites of a PEM fuel cell. Nitrogen was used for this component level test because it was safer than using oxygen and the similarities in these two reactants would produce similar results.

The test matrix was comprised of water and gas flow rates that represented specific fuel cell power levels, O_2 fuel cell consumption rates, and excess O_2 used to entrain the product water. It also represented the four corners of the flow envelope (high gas flow/high water flow; high gas flow/low water flow; low gas flow/high water flow; low gas flow/low water flow) and a mid-level gas and water flow. The matrix is shown below. The O_2 utilization values are defined as:

$$O2 \text{ utilization } (\%) = \frac{O2 \text{ used in fuel cell to create electricity}}{O2 \text{ used to entrain product water}}$$

Power Level (kw)	O2 used in FC (slpm)	H20 produced (ccm)	O2 to water sep (slpm)	O2 utilization (%)
16.5	82	125	100	45
15	75	114	7	91
10	50	76	50	50
5	25	38	2	93
2	10	15	100	9

Each test point was run at 276 and 517 kPa (40 and 70 psia) and at room temperature and 82.2°C (77°F and 180°F). A second room temperature run was sometimes conducted after the 82.2° C runs. The data collection focused on three quantitative measurements—the ΔP across the gas and water membranes and amount of gas in the water outlet—and one qualitative measurement—observed gas in the water outlet stream.

The testing occurred in two 1-g gravity orientations: 1) water separator vertical—with the water outlet endplate (water outlet port and BPR) at the top, the BPR on its side, and the membranes aligned like a stack of disks; and 2) water separator horizontal—with the water outlet port and BPR above the separator and the membranes aligned in an accordion-like fashion (see Figure 4).

Overall, the water separator met all of its requirements during its testing in the vertical position. After one hour of run-time, the separator typically reached a steady-state condition with the gas membrane ΔP < 20.7 kPa (3.0 psid); the water membrane ΔP ~ 0.0 kPa; no water observed in the gas outlet stream, and expected amounts of gas in the water outlet stream—as calculated using Henry's Law. During the high temperature runs, water vapor in the gas outlet stream condensed in a sight glass and collected in the gas outlet manifold. For the first few room temperature runs after the 82.2°C runs, water was seen "showering" through the sight glass—due to this collected water that was picked up by the flowing gas. Also, the higher water membrane ΔPs were seen at the minimum water flow levels. Finally, the high temperatures did not affect the performance of the separator. Trends between room temperature tests and high temperature tests were similar. The higher temperature reduced gas membrane ΔP levels. Since the mass flow was measured

in slpm, a rise in temperature at constant pressure would cause the actual volumetric flow rate to decrease (PV=T)—making it easier for the separator to allow the gas through it membranes.

With the water separator in the horizontal 1-g orientation, the water and gas outlet streams behaved as tested in the vertical orientation. The water membrane ΔP was also typically very low, between 0-6.9 kPa (0.0-1.0 psid) again with the exception of low water flow rates—where the ΔP was closer to 14.8 kPa (2.0 psid).

However, a noticeable increase in the gas membrane ΔP values was observed. The ΔP was as much as 3.5-27.6 kPa (0.5-4.0 psid) higher in the horizontal position. In addition, it seemed that the response of the separator and BPR to the flooded state was slower. For example, it seemed that the large initial spikes, that occurred at the start of a new test point due to changing flow conditions, took longer to decrease. And when it did decrease, many times it did not decrease to < 20.7 kPa (3.0 psid).

This difference may be caused by two possible phenomena: 1) the membrane orientation or 2) trapped water in the gas membrane. Consider a gas membrane disk in the vertical orientation (stacked disks) and in the horizontal orientation (accordion-like fashion). When the separator reaches a flooded state, the gas membrane ΔP rises, causing the BPR to open, and water is released. The water level will decrease until enough gas membrane area is uncovered to allow gas flow across, lower the gas ΔP, and allow the BPR to control water flow. In the vertical orientation, as the water level drops and uncovers an entire flat gas membrane, that entire large gas membrane area will quickly become available for gas to flow across—thus a quick drop in the ΔP. But in the horizontal orientation, as the water levels drops, a small area across several gas membranes will become exposed. This

would continue until enough gas membrane area is uncovered to allow the BPR to control the water flow. If this hypothesis is true, then these effects of orientation will be seen when the separator is run in a 1-g environment. How the separator would perform in a zero-g environment is still undetermined.

A concern raised by the separator manufacturer is that as time goes on, the gas membrane may experience higher ΔP. If happening, this may be the result of water trapped in gas membrane pores. So far, not enough long-term testing has occurred to prove or disprove this theory.

Two other configurations of the water separator have yet to be completed. One will rotate the BPR to determine if its performance is affected by its 1-g orientation. The second will move the BPR to below the water separator—thereby simulating an upside-down, horizontal, 1-g orientation.

IV. CONCLUSIONS

Development of a space-rated PEM fuel cell was proven possible in the Gemini program. The current projections of power system utilization have resulted in a life requirement of 10,000 hours dictating the need to develop reliable components and configurations for not only the fuel cell stack, but also the accessory section. Rigorous analysis, test, and evaluation of both a passive water separator and ejector based reactant pumps are currently underway and nearing completion at the NASA-JSC. Results to date are positive. With the successful integration of these PEM fuel cell building-block elements into the system design currently planned at the NASA-JSC, a significant reduction in the cost and technical risk of developing space-rated PEM fuel cell powerplants will be realized.

V. References

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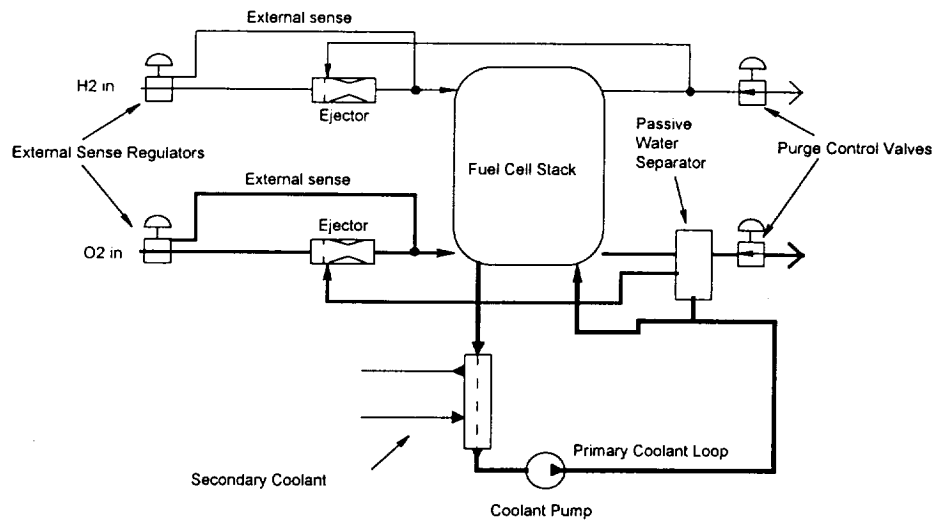
Figure 1 PEM Fuel Cell Powerplant Schematic
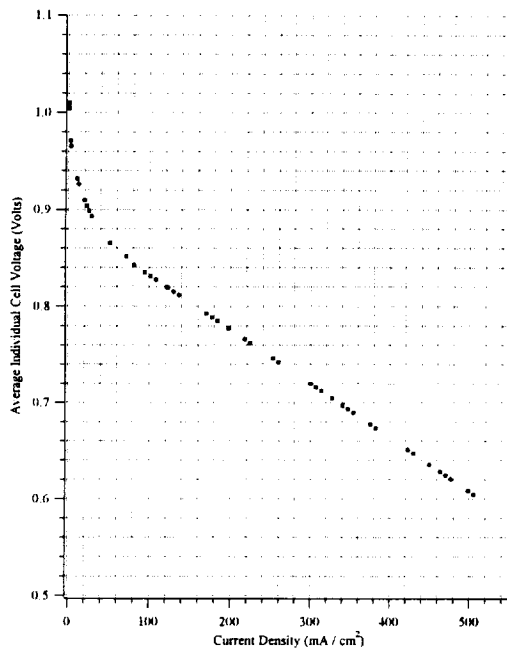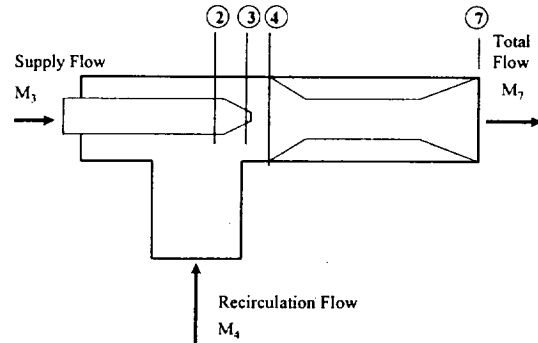

Figure 2 Voltage vs Current Density Curve (typical)

Figure 3
Gas Ejector Schematic
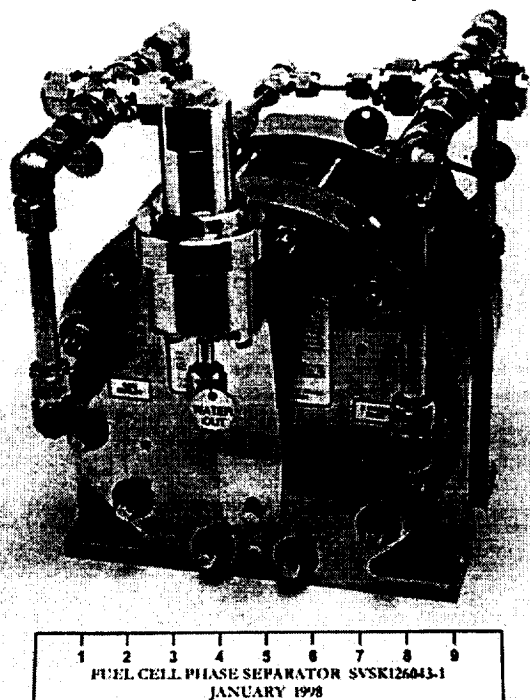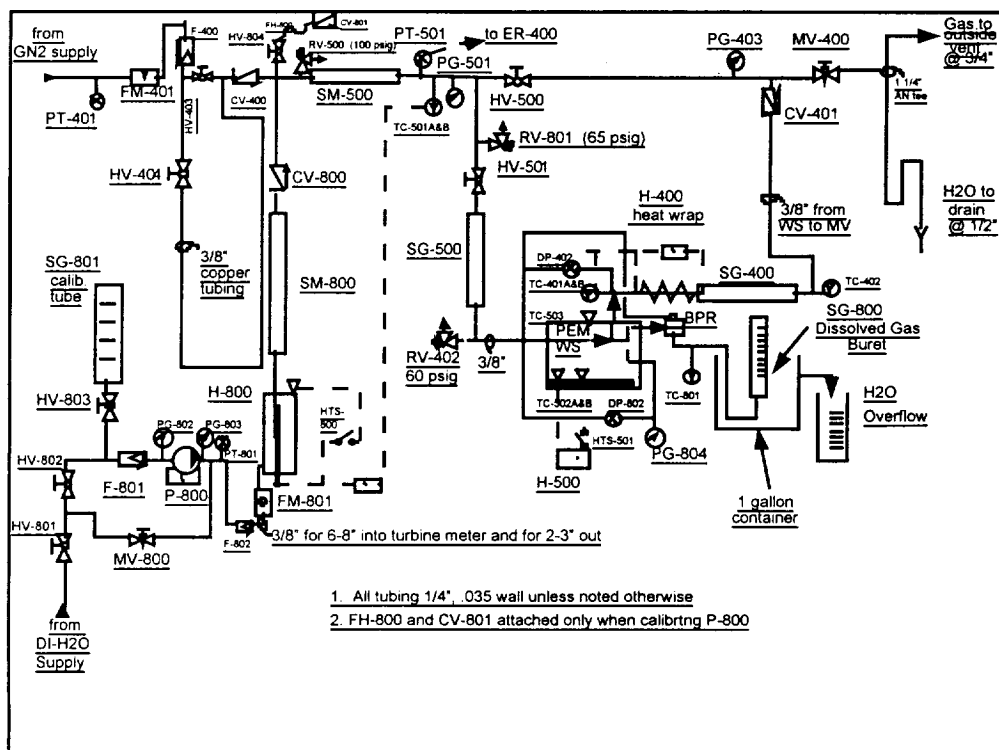
Figure 4
Hamilton Standard Passive Water Separator

Figure 5: Water Separator Test Stand Schematic